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An Assessment of HR Diagram Constraints on Ages and Age Spreads in Star-Forming Regions and Young Clusters

Lynne A. Hillenbrand

California Institute of Technology, 1200 E. California Blvd., Pasadena, CA, 91101

Amber Bauermeister

California Institute of Technology, 1200 E. California Blvd., Pasadena, CA, 91101 and University of California, 601 Campbell Hall, Berkeley, CA 94720-3411

Russel J. White

Department of Physics, University of Alabama - Huntsville, Huntsville AL 35899

Abstract. Pre-main sequence evolutionary theory is not well-calibrated to observations. With care, the observed quantities can be converted into effective temperature and luminosity (i.e. the Hertzsprung-Russell diagram) which the theoretical calculations also predict as a function of stellar mass and age. For a sample of nearby young stellar clusters and associations ranging in age from <1 Myr to >100 Myr, we have tested the loci of luminosity as a function of effective temperature against various sets of predicted pre-main sequence isochrones. As we found in Hillenbrand & White (2004) which tested stellar masses, here for the stellar ages there are two conclusions: some evolutionary calculations fare better than others in reproducing the empirical sequences, and systematic differences between all pre-main sequence evolutionary calculations and the data are apparent. We also simulate hypothetical clusters of varying star formation history and compare the resulting HR diagram predictions to observed clusters. Our efforts are directed towards quantitative assessment of *apparent* luminosity spreads in star forming regions and young clusters, which are often erroneously interpreted as *true* luminosity spreads indicative of *true* age spreads.

1. Introduction

Stars form from giant molecular clouds which become unstable to fragmentation and subsequent collapse of dense cores. Two main theories of star formation suggest different timescales for this process. Ambipolar diffusion (e.g. Shu, Adams, Lizano, 1987) is a quasistatic process that can occur over a range of time scales from just a few million years up to perhaps ten million years. Turbulent dissipation (e.g. Elmegreen 2000) occurs within a much shorter time frame, essentially the dynamical or crossing time which is only several hundred thousand ranging up to a million years, or so, for typical clusters. Accurately estimating the age and age spread of stars in recently formed clusters is one direct means for observationally constraining this formation timescale.

How can the ages of young stars be inferred from observations? Dynamical time scales can be derived based on the spatial distribution and velocity dispersions of young stars in star forming regions, as advocated by Tan et al. 2006 (arguing for slow star formation) and Hartmann et al. 2001 (arguing for rapid star formation). Nuclear burning time scales, such as lithium depletion, can be compared to the theoretical physics of this process as discussed by e.g. Palla et al. 2005 and Jeffries et al. 2005. Stellar structure and atmosphere theory, i.e. the classical HR diagram, is a standard tool for inference of physical parameters of stars having all ages, and has been used in practice by many authors.

It is this last method that is discussed here since the stars suitable for study via the first two methods are only a subset of the sample for which estimates of effective temperature and luminosity are now available in the literature. The HR diagram has many shortcomings, elucidated below. However, making use of the tools one has and recognizing their limitations is better than both alternatives: not making progress at all, on the one hand, and, on the other, overstating our understanding of pre-main sequence evolution in young clusters due to a lack of attention to caveats and limitations of employed methodology.

2. The Data

The axes of the HR diagram, log $L/L_\odot$ and log T_{eff}, remain difficult to determine with high precision for star forming regions. Such quantities are derived from two sets of observations. First, typically low resolution optical (usually in the V or I bands) or near-infrared (usually in the J or K bands) spectroscopy measures photospheric emission and can be used for spectral typing and thus, in combination with a gravity/metallicity dependent temperature scale, for temperature estimation. Second, optical or near-infrared photometry is compared with intrinsic colors estimated from the spectral type, and used to infer foreground extinction. The appropriate bolometric correction is then applied to reddening corrected photometry and a stellar luminosity is thus derived. Seemingly straightforward, this process of course suffers many challenges in practice.

A recent example of the observational complications is provided by comparison of data from an HST wide-field ACS survey of the Orion Nebula Cluster (Robberto et al. 2006) with older ground based data (Hillenbrand 1997) which shows considerably larger photometric scatter. This is no doubt due to a combination of the large dynamic range in source brightness, the crowding of point sources, and the bright and spatially variable nebular background, all of which can bias photometric data having relatively larger point spread function. High data quality that can counteract the many observational challenges presented when working in regions of recent star formation is a primary consideration in the quest for high fidelity age estimates from HR diagrams.

Further astrophysical, rather than mere observational, complications for young star cluster photometry include: random effects of photometric variability, systematic effects of activity/disks, and systematic effects of spatially unresolved binaries. Each is an interesting area of study in its own right, but here we lump all such astrophysical effects into the observational error terms. This results in errors in effective temperatures and luminosities that are larger than the formal

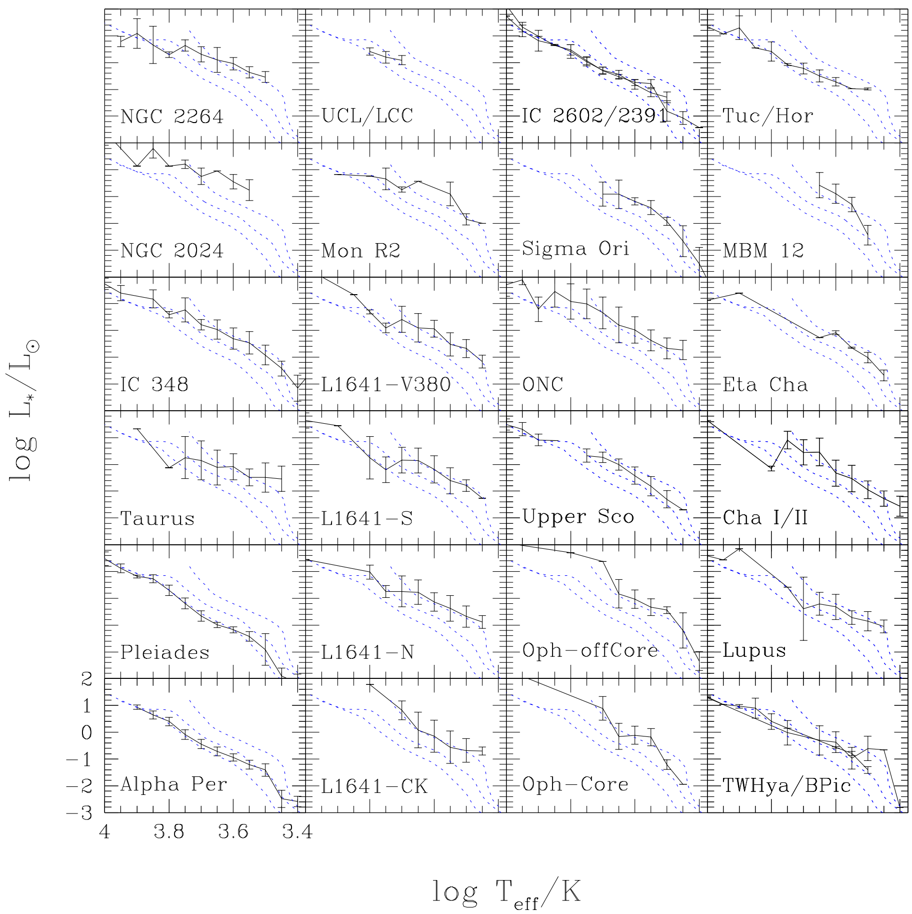

Figure 1. Representations of young star cluster luminosity spreads. Median and 1-sigma luminosity as a function of effective temperature, shown for spectral types cooler than A0 (masses <3 $M_{\odot}$). Comparison of the empirical isochrones (solid lines) is made to the 1, 10, and 100 Myr constant age sequences from D'Antona & Mazzitelli (1997/1998; dotted lines).

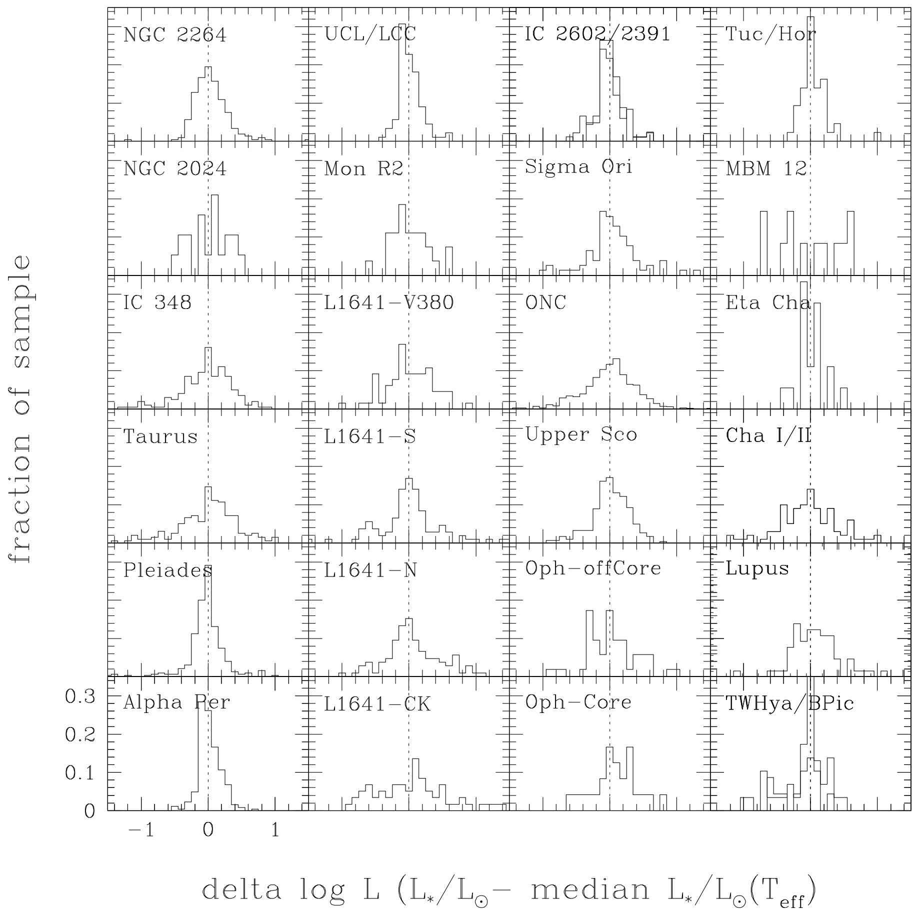

Figure 2. Representations of young star cluster luminosity spreads. Luminosity dispersion calculated for individual data points around the median luminosity at each effective temperature from the left panel. These histograms collapse the two dimensional information of the HR diagram into one dimensional distributions, thus absorbing any trends in luminosity dispersion with mass.

errors in these quantities one would estimate by simple error propagation from the observed quantities (spectral types and photometry).

Without, for the moment, consideration of the above observational and astrophysical error terms and their effects on young star temperatures and luminosities, what do we find when we assemble the HR diagrams for all well populated and well studied recently star forming regions and young open clusters in the solar vicinity? As we discuss in detail in a forthcoming paper, there is variety in the richness levels in the known populations, as well as in data quality. Nevertheless, a composite of such HR diagrams clearly illustrates an age progression among the clusters from <1 to 120 Myr, this via the decrease in mean/median luminosity due to the contraction of individual cluster members towards the zero age main sequence. Because of the large number of data points, the main loci of points are easier to see by considering the median luminosity as a function of spectral type and the dispersion about this median (Figure 1) or the detailed luminosity distribution about this median (Figure 2).

In what follows we discuss such representations of the data relative to predictions for simulated clusters. The main question we aim to address is: do observed luminosity spreads correspond to age spreads, or are they consistent with error distributions created from the combined observational and astrophysical contributions to stellar luminosity error terms?

3. The Isochrones

Before we begin our assessement, a pre-cursor question to be answered is: do theoretical pre-main sequence evolutionary tracks correctly predict stellar ages? Given that the available models have considerable differences in their predictions of effective temperature and luminosity at a given mass and age, which should we believe?

There are at least 6 different groups with published pre-main sequence evolutionary calculations that have been widely circulated in machine-readable formats and that span a suitable range of stellar masses. For these, listing only the most recent reference for each group – Swenson et al. 1994 (S93); D'Antona & Mazzitelli 1997 with 1998 electronic-only update (DM98); Siess et al. 2000 (S00); Baraffe et al. 1998 (B98) with Chabrier et al. 2000; Palla & Stahler 1999 (PS99); and Yi et al. 2003 (Y^2) – the differences in assumptions, included physics, and methods are broadly outlined in Hillenbrand & White (2004) which assessed the consistency of these models with available dynamical mass estimates. Here, we focus on the age predictions of these same models.

We can assess the systematic trends between the various sets of tracks by considering the predictions for some fiducial stars of given temperature and luminosity. Figure 3 compares the ages inferred for young solar-type and low-mass members of several young clusters as modelled with the 6 sets of tracks. For the sub-solar mass stars, systematic effects between the tracks are observed at the level of 0.75 dex at the youngest ages; cluster age estimates are, therefore, strongly dependent on which set of pre-main sequence evolutionary theory is adopted. For the solar-mass stars the agreement is better, particularly towards older pre-main sequence ages.

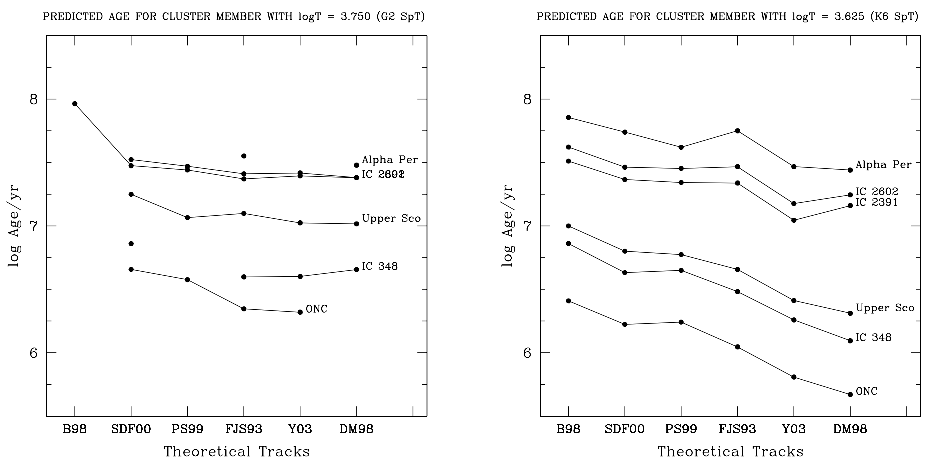

Figure 3. Systematic trends in predicted stellar ages for G2 (left panel) and K6 (right panel) stars having the median luminosity of the indicated clusters at those spectral types. Two effects are apparent. First is variation in ages predicted by different sets of pre-main sequence evolutionary tracks for the same value of log $L/L_{\odot}$ and log T_{eff}. Towards older ages especially, the G2 star predictions are relatively flat indicating that the models are fairly consistent with one another; the K6 star predictions, however, show considerably more variation between the models. Second are the different ages predicted between the left and right panels for stars which lie along the same empirical isochrone (i.e. same age) but are of different spectral type (i.e. different mass). Specifically, in Upper Sco the G2 stars have predicted ages somewhat older than 10 Myr, fairly uniformly among the tracks, while the K6 stars are 2-10 Myr depending on track choice.

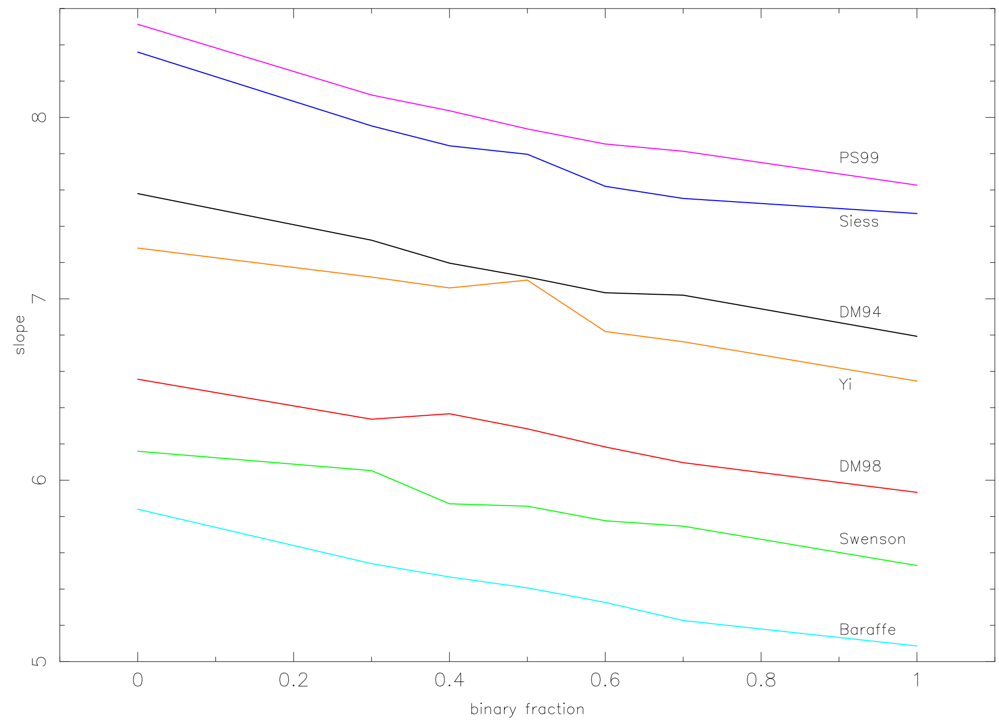

Figure 4. Change in "slope" of the simulated HR diagram, simply δ log $L/L_{\odot}$ / δ log T_{eff} calculated in four bins of width 0.05 dex from log $T_{eff} = 3.55 - 3.70$, as a function of the binary fraction for a simulated 5 Myr old cluster. Each line represents a different pre-main sequence evolutionary model, as labelled.

Putting the systematics between the tracks aside, for all tracks, the higher mass stars are predicted to be older than the lower mass stars in the same clusters. This effect often has been ascribed to the influence of the "stellar birthline" (Stahler 1983; Hartmann, Cassen, & Kenyon 1997). However, comparing the left and right panels of Figure 3 reveals that the observed age-with-mass trend persists longer than the influence of birthline effects is expected to last.

4. Comparison of Simulated and Empirical Isochrones

In order to assess empirical ages and age spreads derived from HR diagrams, we have created a suite of simulations that probe our ability to distinguish true age spreads from observational and astrophysical noise. We use three diagnostics:

- the slope of the HR diagram, that is, $[\delta(\log L/L_{\odot})/\ \delta\ (\log T_{eff}/\mathrm{K})]$ calculated from the median luminosity as a function of effective temperature;
- the dispersion (σ) of the individual stellar luminosities measured around the median luminosity at the same effective temperature;
- the detailed luminosity distribution around the median luminosity at the appropriate effective temperature;

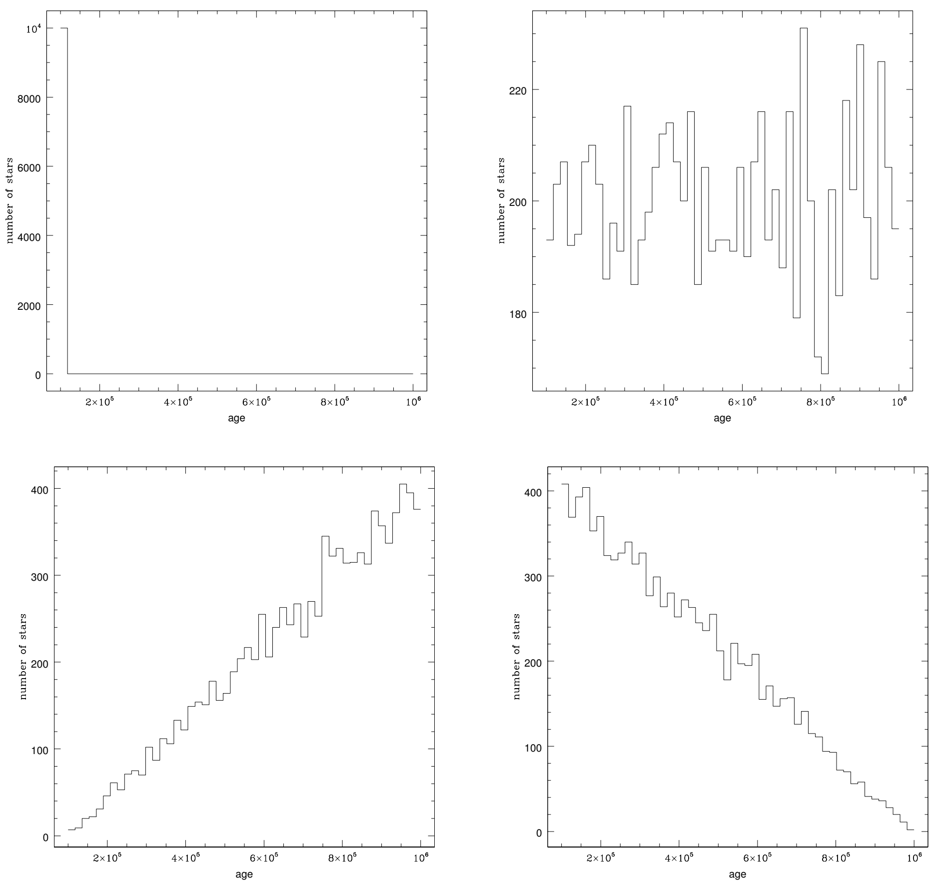

Figure 5. Simulated star formation histories: burst, constant, and linearly increasing/decreasing shown as number of stars formed vs time in years. Scatter represents numerical noise for a simulation consisting of 10,000 stars.

Roughly speaking, the clusters of Figure 1 follow empirically a linear relation in log luminosity versus log temperature, at least over the temperature range illustrated. In Figure 4 we show that the linear slope calculated for simulated HR diagrams of given age not only varies between theoretical tracks, but is a strong function of the binary fraction. For an assumed age of 5 Myr appropriate to the Upper Sco association, one might conclude from Figure 4 that in comparison to the "observed" slope for this cluster of 7.26, the Siess et al. tracks provide the best description of the data for a binary fraction near unity, while the Yi et al. tracks are best if the binary fraction is closer to zero; the D'Antona & Mazzitelli tracks might be appropriate for intermediate binary fractions.

Distinctions between young clusters are seen not only in these slopes, which represent the averaged empirical isochrone, but also in the detailed luminosity distribution about the median with effective temperature, which potentially represent age true age dispersions. As was illustrated in Figure 2, while some regions are reasonably well-described by gaussian luminosity distributions about the median value, suggesting that their luminosity spreads are consistent with errors, other regions show a distinct step-like progression in the luminosity distribution towards higher luminosities with a sharper fall-off in the distribution towards lower luminosities. This form is most consistent with the expectations for a binary influence on the luminosity distribution, as illustrated below.

To investigate in more detail the consistency of observed luminosity spreads with true age spreads, we employ a monte carlo methodology to populate theoretical pre-main sequence evolutionary tracks. In our illustration of the technique here, we adopt the Siess et al. tracks as our fiducial set. Included in our simulations are a mass distribution (default assumption is standard Miller-Scalo IMF) and a multiplicity fraction (default assumption is 40% with secondaries drawn either from the IMF or from a simple functional form in $q = m_2/m_1$).

Our main goal is to understand what can be inferred about star formation histories from empirical data converted into an HR diagram. Thus we have simulated various renditions of the sequence of star formation with time in the observed young clusters. We consider burst (no age spread) scenarios as well as a constant rate of star formation with time and linear or exponentially increasing and decreasing functions, as illustrated in Figure 5. Example results for these star formation histories are shown in the simulated but error-free HR diagrams of Figure 6. Finally, we add observational errors (uniform or gaussian) as the last step before creation of the HR diagram or of a histogram of the distribution of luminosity about the median luminosity run with effective temperature.

5. The Findings

Having presented the data and our simulation methods, we proceed now with some illustrative simulation results. In Figures 7 and 8 we show the distribution of individual simulated luminosities about the median luminosity appropriate to the relevant simulated effective temperature.

In the case of Figure 7 we are testing various star formation scenarios containing an 80% age spread (that is, for a cluster of median age 1 Myr, the youngest stars are only 0.2 Myr old and the oldest are 1.8 Myr old) against a 0% age spread or a "burst" star formation scenario. The "core" in the delta-

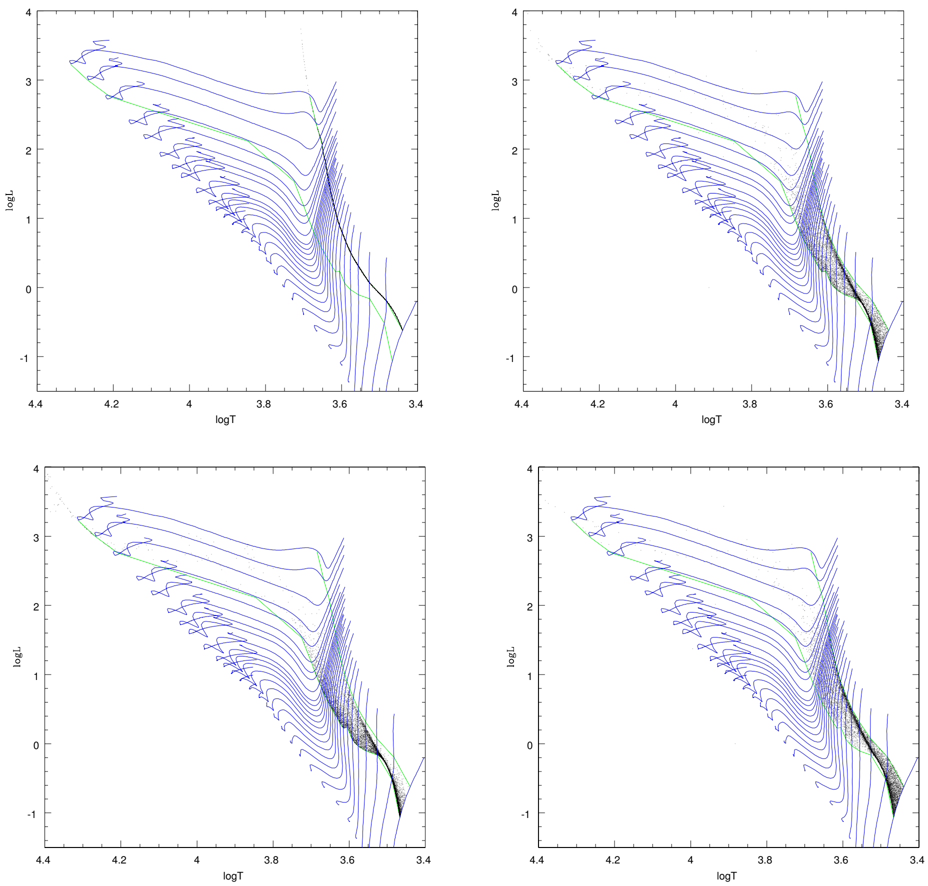

Figure 6. Simulated HR diagrams in standard units for the burst, constant, and linearly increasing/decreasing star formation histories of Figure 5, using the Siess et al. (2000) tracks. Mass tracks and isochrones at the start and end of the simulated age range are shown, along with 10,000 simulated points.

log$L$ distribution is due to the assumed error distribution (here 0.1 dex), the high log$L$ tail is due to the assumed binaries (40% fraction), and the broad wings are indicative of the inserted age spread. To quantify what is visible by eye, we employ the Kolomogorov-Smirnov (KS) test which produces the probability that two distributions are drawn from the same parent distribution. Here, except in the case of the burst scenario, the KS test rejects that the input age spread produces the same luminosity spread as the burst case.

In Figure 8 we look at the ability of the simulations to distinguish multiplicity fraction. Specifically, we test a 40% binary, coeval population fiducial sample against populations with a mere 10% age spread and different binarity fractions. The histograms indicate a narrow excess in the 0% binaries panel relative to the fiducial, and a broader excess in the 70 and 100% binaries panels. Here, the KS test finds that the 0, 70, and 100% binaries cases are rejected as being drawn

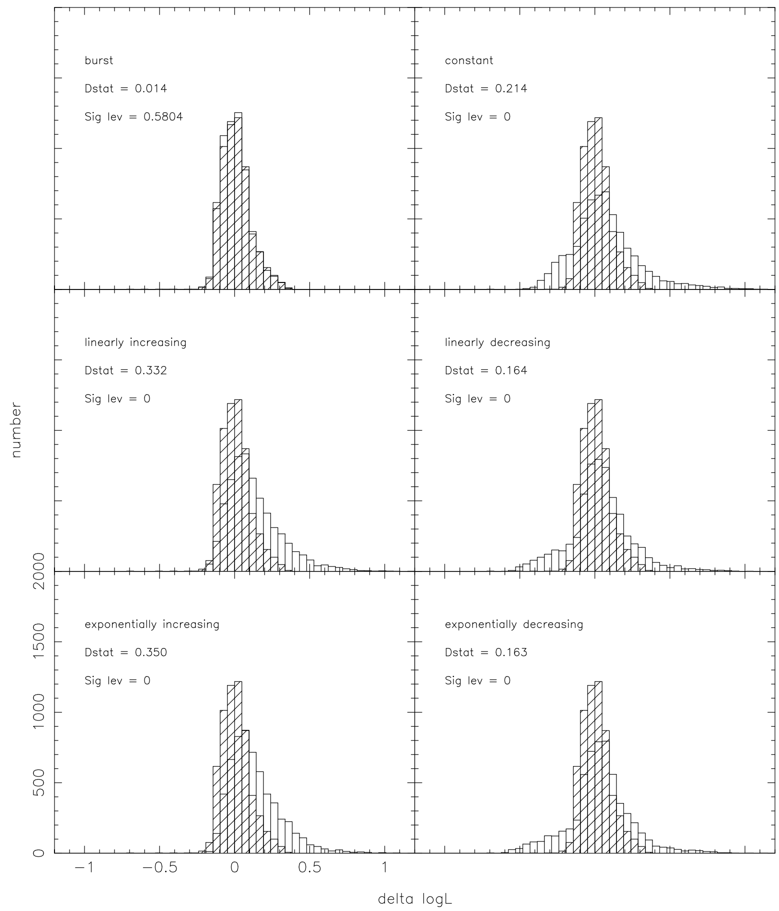

Figure 7. Simulated luminosity spreads (solar units), including effects of true age spread plus observational error (open histograms) compared to burst or no age spread scenario, with error (hatched histogram, same in each panel). The KS "D statistic" representing the maximum difference between the cumulative distributions and its significance level are given. Upper left panel represents two realizations of the same star formation scenario and thus illustrates the magnitude of numerical noise. In all other panels the KS significance is better than one percent, suggesting we can distinguish the scenarios.

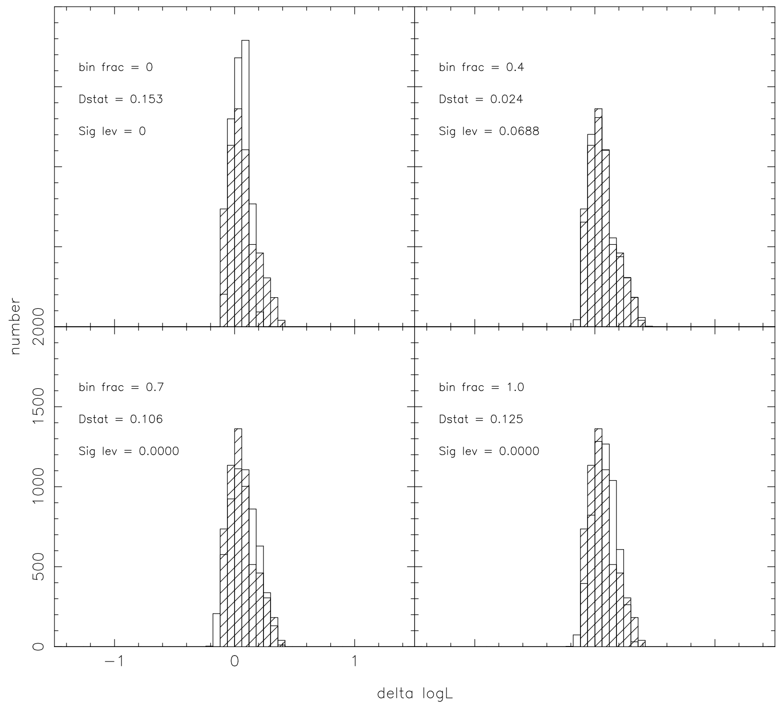

Figure 8. Simulated luminosity spreads (solar units) for a 40% binary fraction population from a "burst" (no age spread) star formation episode 2 Myr ago including observational errors (hatched histogram, which is the same in all panels). This is compared to populations having binary fraction 0, 70, and 100% all with a constant rate of star formation and 10% age spread around a mean age of 2 Myr (open histograms). The upper right panel is thus not just two realizations of the same binary fraction; the KS test finds that these cases still have a 7% chance of being the same. In all other panels the KS significance is better than one percent, arguing that binary properties can be detected against the background of small age spreads.

from the same population, while the two 40% binary fractions have reasonable chance of being from the same parent.

The question at hand is whether we can distinguish age spreads from either the details of the star formation history or from the mulitiplicity effects. To test this we have run a large number of simulations at median ages of 2, 6.5, 10, and 20 Myr and calculated the KS significance of the input fractional age spread compared to a zero percent age spread. Based on the decline of the KS statistic, where small implies distinguishable distributions, we conclude from Figure 9 that when observational errors are modest (±10% on stellar luminosities), age spreads larger than ∼10-15% can be distinguished.

How good do the empirical luminosities really need to be? More or less, the above scaling is roughly correct. At 1-10 Myr absolute ages, 30% luminosity errors mean that at best 30% age spreads can be distinguished from 0% age apreads; however, 30% age spreads can not be distinguished from 5, 10, 20,

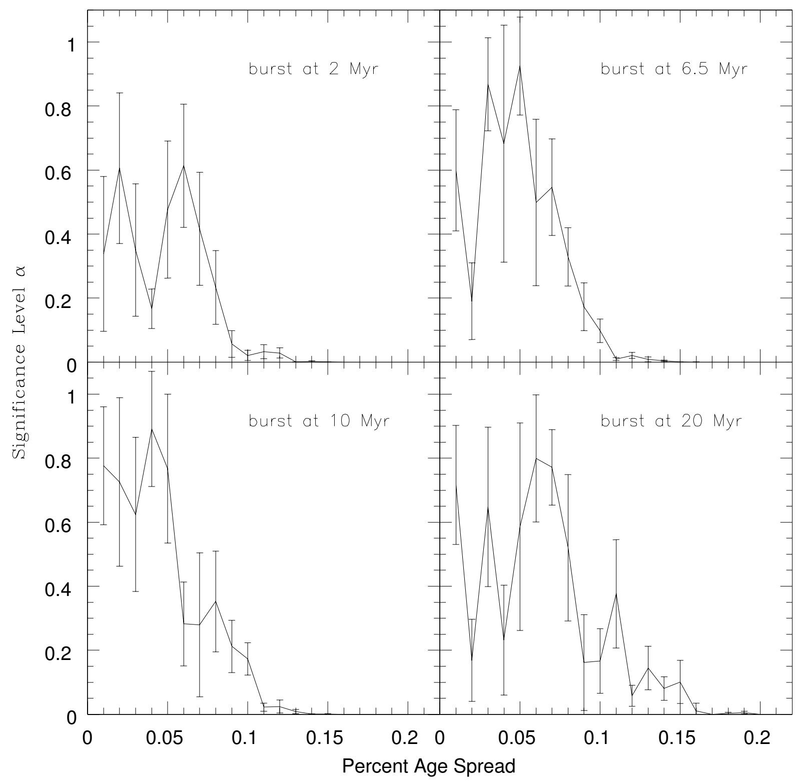

Figure 9. Results of KS tests. The decline towards zero indicates that an age spread of the indicated fraction along the abscissa – *not percent, as incorrectly labelled* – of the fiducial age (2, 6.5, 10, or 20 Myr depending on the panel) is distinguishable from a burst model having an error distribution with maximum amplitude 0.1 mag. Vertical bars indicate the dispersion amongst 100 simulations having each age spread.

40, or 50% age spreads. Our current work is to quantify more usefully our conclusions regarding observational errors and cluster age spreads.

6. Summary and Implications

In summary, we offer a few simple cautions regarding stellar models and physical parameters derived from classical HR diagrams. First, pre-main sequence evolutionary tracks: 1) vary between theory groups; 2) under-predict stellar masses by 30-50% (as assessed in White and Hillenbrand, 2004); 3) under-predict low-mass stellar ages by 30-100%; and 4) over-predict high-mass stellar ages by 20-100%. These findings imply large systematic uncertainties in: cluster initial mass functions, cluster age distributions, and hence star formation histories in molecular clouds as well as disk and angular momentum evolutionary time scales.

From our study of young star luminosities we have found useful diagnostics in the HR diagram slope, the median luminosity as a function of effective temperature, and the simple dispersion as well as the detailed shape of the normalized luminosity function about the median run with effective temperature. From our simulations we conclude that observed HR diagram slopes can inform track choice modulo binarity and that KS tests of luminosity distribution about median can distinguish: multiplicity fraction, star formation history, and even true age spreads given small enough observational errors.

Finally, we conclude based on our (in)ability to distinguish signal from observational and astrophysical noise in the HR diagram, that at present there is only marginal, i.e. no strong, evidence for moderate age spreads in recently star forming regions and young open clusters (see also, Hartmann 2001). These findings are consistent with the decades old – but unheeded – warnings on young cluster HR diagrams that were issued by Larson (1972) on their utility for understanding pre-main sequence evolution, and by Mercer-Smith et al. (1984) on the interpretation of luminosity spreads as true age spreads.

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